

The Expanded Very Large Array

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ABSTRACT

In almost 30 years of operation, the Very Large Array (VLA) has proved to be a remarkably flexible and productive radio telescope. However, the basic capabilities of the VLA have changed little since it was designed. A major expansion utilizing modern technology is currently underway to improve the capabilities of the VLA by at least an order of magnitude in both sensitivity and in frequency coverage. The primary elements of the Expanded Very Large Array (EVLA) project include new or upgraded receivers for continuous frequency coverage from 1 to 50 GHz, new local oscillator, intermediate frequency, and wide bandwidth data transmission systems to carry signals with 16 GHz total bandwidth from each antenna, and a new digital correlator with the capability to process this bandwidth with an unprecedented number of frequency channels for an imaging array. Also included are a new monitor and control system and new software that will provide telescope ease of use. Scheduled for completion in 2012, the EVLA will provide the world research community with a flexible, powerful, general-purpose telescope to address current and future astronomical issues.

Subject headings: Radio telescope; radio astronomy; aperture synthesis; wide-band RF systems; low-noise receivers; low-noise amplifiers; orthomode transducers; corrugated feed horns; frequency synthesizers; IF downconverters; digital data transmission; digital correlator

1. Introduction

The Very Large Array (VLA) is an imaging array located on the plains of San Augustin in west-central New Mexico. It consists of a total of 27 antennas, each 25 meters in diameter, with nine antennas distributed along each of three equilateral arms extending out to 21 km from the center. The array provides diffraction-limited images of astronomical objects in all Stokes parameters, with a maximum resolution at 1.4 GHz of 1.4 arcseconds, and at 45 GHz of 0.05 arcseconds. Detailed descriptions of the VLA as originally constructed can be found in [1] and [2].

The VLA was designed and built in the 1970s, and utilized the best technology of that time. The telescope, upon completion in 1980, could observe in four frequency bands, utilizing state-of-the-art cryogenically cooled receivers, TE₀₁ circular waveguide to transport the analog signals of 200 MHz bandwidth from the most distant antennas to the central location without amplification and, most notably, a digital correlator capable of producing up to 512 spectral channels spanning 3 MHz for each of the 351 baselines, or full-polarization continuum correlations at two frequencies simultaneously with 50 MHz bandwidth. The VLA increased astronomical capabilities by one or more orders of magnitude over all preceding radio telescopes in sensitivity, resolution, frequency coverage, speed, flexibility, and imaging fidelity.

The design of the VLA was heavily influenced by both the available technology of the 1970s, and the key scientific questions of that era, which included imaging the Doppler-shifted emission from neutral hydrogen from local galaxies and resolving the bright continuum emission of distant quasars, radio galaxies, and supernova remnants. The VLA has been spectacularly successful both in addressing these questions, and in its application to a wide range of astrophysical problems unknown or unanticipated in the 1970s. It has been so successful in this latter area because it was designed as a general purpose, reconfigurable array. However, the VLA has changed very little since 1980. Although most of the receiver bands have seen improvements in sensitivity, and four new receiving systems have been added, the array’s original signal transmission system and correlator remain unchanged. In the approximately 30 years since the VLA was designed, there have been enormous advances in technology, particularly in digital communication and signal processing capabilities. Over the same interval, the key scientific questions have also undergone great changes, requiring telescopes with ever greater emphasis on sensitivity, wider frequency coverage, faster surveying capabilities, more spectral capabilities, higher imaging fidelity, and faster response to transient emission. One can respond to these challenges in two ways: by designing wholly new instruments, or by utilizing modern technologies to upgrade, and expand, the world’s preeminent existing telescopes. Taking the latter approach has resulted in the Expanded

Very Large Array (EVLA) project.

The technical requirements for the EVLA are based on a comprehensive review of the potential science enabled by order of magnitude, or greater, improvements over existing VLA capabilities. There are four major science themes for the EVLA:

- The Magnetic Universe: Measuring the strength and topology of magnetic fields,
- The Obscured Universe: Enabling unbiased surveys, and imaging of dust-shrouded objects which are obscured at other wavelengths,
- The Transient Universe: Enabling rapid response to, and imaging of, rapidly evolving transient sources, and
- The Evolving Universe: Tracking the formation and evolution of objects in our universe, ranging from stars to spiral galaxies and galactic nuclei.

For all of these themes, it was readily demonstrated that order-of-magnitude improvements in VLA performance by implementation of modern technologies will result in spectacular new science by the world user community. The EVLA is a comprehensive technical upgrade of the VLA. It is a leveraged project: by utilizing relatively inexpensive modern digital electronics, and building on the existing infrastructure of the VLA, the EVLA will advance by one to four orders of magnitude all the imaging capabilities of the VLA at modest cost and in a time short compared to that needed to design and build a new facility. The EVLA will provide astronomers a modern, general-purpose, radio telescope capable of addressing the key scientific issues of the day, and the yet-unforeseen issues of the future.

The EVLA project was started in 2001. The new correlator will be installed in 2009, the conversion of the VLA antennas to the EVLA design will be complete in 2010, and all receivers will be installed by 2012. The entire project will be complete in 2012. The project is funded by the National Science Foundation of the United States of America, the National Research Council of Canada, and the Consejo Nacional de Ciencia y Tecnologia of Mexico.

An overview of the system is described in Section 2. A more detailed description of the instrument's major subsystems, including feed horns and receivers, local oscillator, intermediate frequency, and data transmission systems, and software, is given in Section 3. The paper is summarized in Section 4. The descriptions of acronyms used throughout the paper are listed in the Glossary.

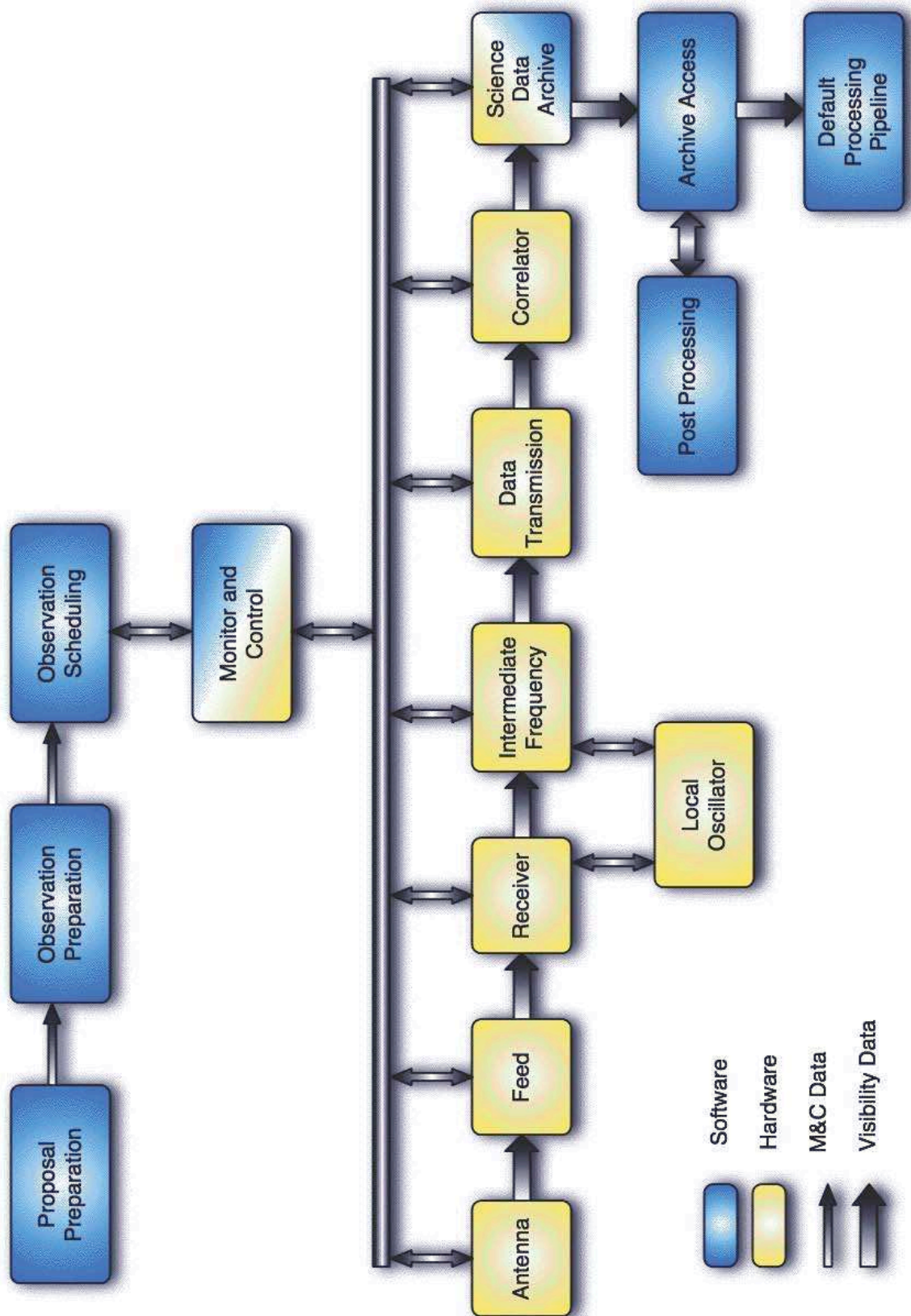


Fig. 1.— Simplified block diagram for the EVLA

2. System Overview

The primary technical requirements for the EVLA that were determined from the instrument’s scientific goals are:

- New or upgraded receivers at the Cassegrain focus of the antennas providing continuous frequency coverage from 1 to 50 GHz in 8 frequency bands (see Table 1).
- A new, wide bandwidth, fiber optic data transmission system, including associated local oscillator (LO) and intermediate frequency (IF) electronics, to carry signals with 16 GHz total bandwidth from each antenna to the correlator.
- New electronics to process 8 signal channels of up to 2 GHz bandwidth each.
- A new, wide bandwidth, full polarization correlator providing at least 16,384 spectral channels per antenna pair (baseline). The correlator provides full polarization capability for four polarization pairs of input signals of up to 2 GHz bandwidth each.
- A new real-time control system for the array and new monitor and control hardware for the electronics system.
- New high-level software that will provide ease of use of the EVLA to its users.

A simplified block diagram for the EVLA, showing the relationship between the major hardware and software sub-systems designed to meet these technical requirements, is shown in Figure 1. Details of the subsystems are provided in the sections below, but at this point we note that six top-level constraints influenced the design of the EVLA sub-systems:

- New systems must have a compatibility mode which allows continued observations with them during the transition period when the old VLA systems are still in use. This constraint particularly impacted the monitor and control software which had to be compatible with the original Modcomp computer-based system of the VLA and the new digital data transmission system which had to provide a means of re-generating the four, narrow band, IF signals required by the VLA correlator.
- New systems must be designed to work with those parts of the old system which were to be re-used. The dominant impact here was on the feed and receiver subsystems where the decision to re-use the VLA antennas and their optics forced the new feeds to be designed for the existing subreflector illumination angle of 18° (full angle).

- The old analog IF transmission system was to be replaced with a digital IF transmission system in order to provide improved bandpass stability as well as an increased bandwidth. The bandwidth required to provide digital transmission of 16 GHz of bandwidth per antenna required the replacement of the original VLA waveguide system with fiber optics.
- A design to minimize the impact of radio frequency interference (RFI) was particularly important for two reasons. The decision to digitize the IF signals at the antenna placed a large amount of high-power, high-speed digital circuitry very close to the high sensitivity receivers. Consequently, the feeds and receivers were designed with shielding against RFI coming from within the receiver cabin, and the electronics modules of the monitor and control, IF, LO and digital transmission systems used components designed to minimize RFI. These components were located inside custom-built, RFI-tight enclosures. Additionally, the requirement to have continuous frequency coverage in the receivers from 1 to 50 GHz meant that the signals from a number of strong sources of external RFI, such as radars and communication satellites, are present in some of the receiver bands requiring a design to minimize the impact of external RFI. Measures taken here included high headroom in the receiver chains, up to 8 bits of resolution in the IF digitizers, the provision of high spectral dynamic range in the correlator, and the option to include narrowband stop filters in the RF.
- The software must all be loosely coupled, allowing access to all the separate subsystems without interdependencies between them, so that the entire system can continue to function although a particular subsystem may not be functioning.
- Information flow in the software system must occur with as little human intervention as possible, to facilitate ease of use for users, to minimize the manpower required to operate the system, and to minimize errors in data transcription by people.

3. Major Subsystems

3.1. Front End Systems

One of the major goals of the EVLA project is to provide continuous frequency coverage between 1 and 50 GHz from the secondary focus with an improved gain-system temperature quotient (G/T) and up to 8 GHz of instantaneous bandwidth in each of two, orthogonal, circularly-polarized channels. A number of novel wide-bandwidth technologies had to be employed to achieve these requirements.

The 1-50 GHz coverage is an increase of almost a factor of five over the coverage provided by the VLA and is broken up into the eight receiver bands shown in Table 1. Also listed are the goals for system temperature, antenna aperture efficiency, and effective system temperature. The system temperatures are based on an assumption of good weather and are mid-band estimates. Values at the band edges are typically degraded by up to a factor of two.

3.1.1. *Feed Horns*

A new feed cone at the secondary focus of the telescope was designed to accommodate the eight feed horns and receivers. All the feeds are located near the vertex of the primary reflector on a circle of radius 97.54 cm centered on the reflector axis. An offset Cassegrain geometry is used so that the secondary focus lies on this circle. Changes in observing band are made by rotating the subreflector to redirect the reflected radiation to the desired feed horn.

The octave bandwidth feeds for L, S and C-bands use compact profile corrugated horns [3]-[7]. In the compact horn design, the transition from the throat to the aperture uses a cosine taper. As a result, the horn is shorter in length by 30% when compared to a linear taper horn, and the aperture of the horn is about 25% smaller. A G/T analysis at 3 GHz determined that the optimum illumination taper at the edge of the subreflector for the EVLA antenna would be -17 dB. The limitation of space around the feed circle precluded the use of feeds large enough to accomplish this at the lower frequency bands. As a compromise, a taper of -13 dB was selected for S and C-bands resulting in smaller feeds with G/T reduced by only 10%. For L-band, a taper closer to -10 dB was selected because the feed had to be about 20% smaller in size to fit in its slot on the feed circle without requiring structural modifications to the antenna backup structure. This structural limitation is the reason for the lower aperture efficiency of the L-band receiving system (Table 1). The original VLA L-band feed is a hybrid, lens-corrected design, and has a higher G/T than the new design over its narrower 1.3-1.8 GHz frequency range at elevation angles above 60°. However, the new design has superior performance across its 1-2 GHz bandwidth below 60° elevation due to a reduced forward spillover that gives less pickup from the ground. For the higher frequency bands (X, Ku, K, Ka and Q-bands), the feed designs are based on corrugated horns with a linear taper [8].

In order to obtain a good impedance match over these broad frequency ranges, especially the octave bandwidths needed at L, S and C-bands, ring-loaded corrugations are used in the mode converter section of each horn [9]. The mode converter provides for a good match

between the corrugated and uncorrugated waveguides at the input of the receiver. The diameter at the last corrugation is small enough to prevent the excitation of the unwanted EH₁₂ mode. The HE₁₁ mode in the corrugated section is converted to the TE₁₁ mode in the circular waveguide. The mode converter, depending on the frequency band, has six to eight ring-loaded corrugations.

All of the EVLA feed horns perform satisfactorily. Cross-polarized sidelobes are found to be below -25 dB. The measured return loss on the higher frequency horns is better than -25 dB. The lower frequency, compact horns exhibit a return loss better than -25 dB over most of their frequency range, dropping to about -18 dB at the low end of each band.

3.1.2. Receivers

The EVLA project requires 240 new or upgraded receivers in total (8 receiver bands for 28 antennas and 2 spares). Existing VLA K and Q-band systems were upgraded with the latest low-noise cryogenic amplifiers and a new, broadband, RF/IF downconverter scheme to provide bandwidths up to 8 GHz. The new L, C, X and Ku-band receivers replace older VLA systems which were both narrowband and less sensitive. The S and Ka-band receivers are brand new systems. The existing 74 MHz (“4-band”) and 327 MHz (P-band) receivers at the prime focal point of the antennas remain in place and are not modified as part of the project. A block diagram of the EVLA Ka-band receiver, which is similar in overall design to the devices used at the other EVLA receiver bands, is shown in Figure 2.

Circular Polarizers

All of the receivers accept dual, circularly polarized, signals. The L, S and C-band systems use quad-ridged orthomode transducers (OMTs) to separate the orthogonal linearly polarized components of the signal [10]. The design of an OMT with an octave bandwidth, a return loss better than -15 dB and which contains no trapped-mode bandpass features was a challenging development effort. This work was carried out at the National Radio Astronomy Observatory (NRAO). The mechanical design of the OMT also had to be one that was low cost and which could be easily fabricated and assembled in production quantities with minimal tuning adjustments. A further challenge was that the OMT needed to be small enough to be cryogenically cooled to reduce the noise contribution from inevitable ohmic losses. The OMT designs were extensively analyzed and optimized using theoretical models and finite-element electromagnetic simulation tools. Extensive parametric analyses were carried out to determine the most critical dimensions and to set fabrication tolerances.

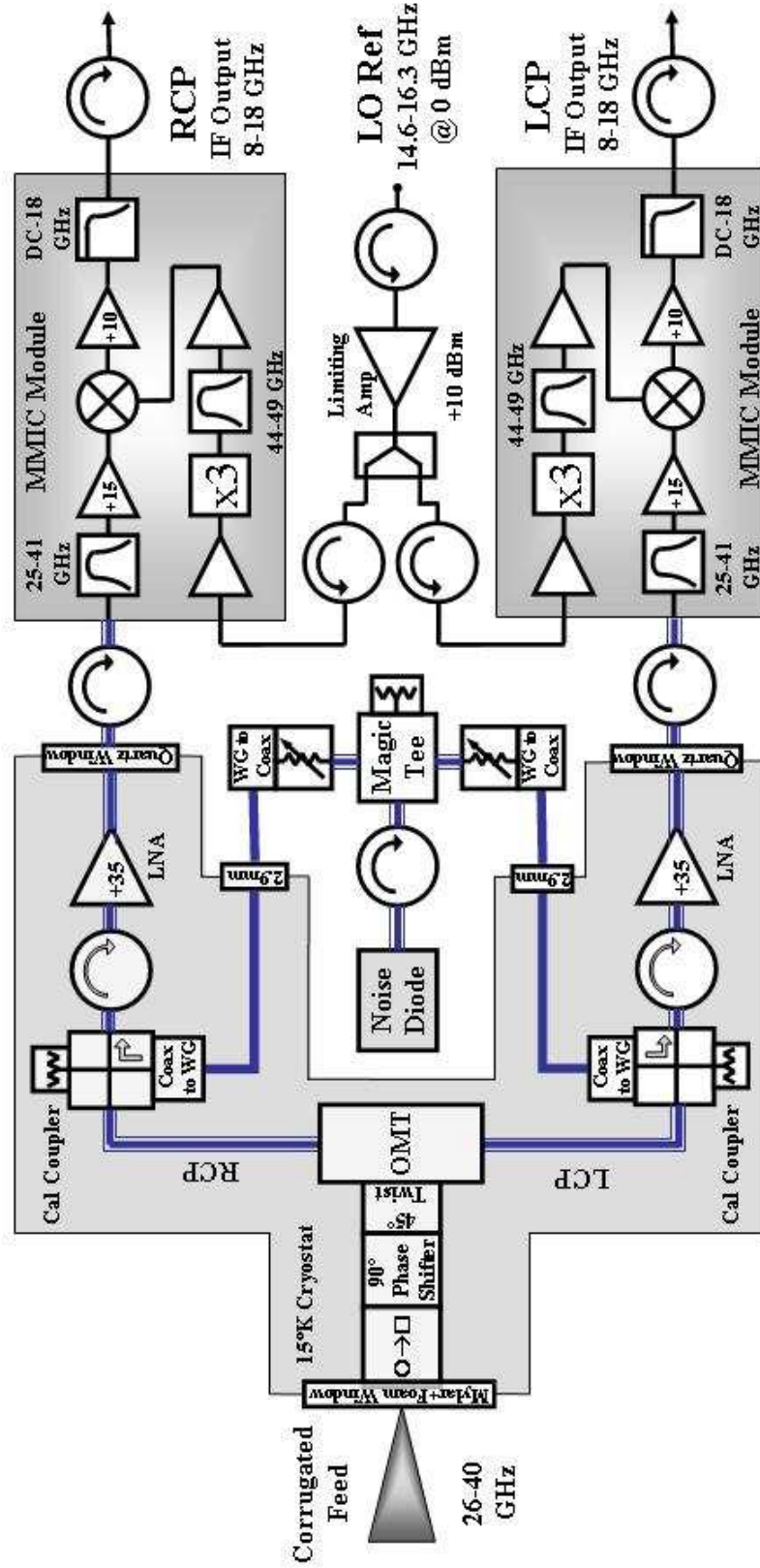


Fig. 2 Block diagram of the EVLA K-band receiver

The quad-ridge OMT must match the impedance of the circular waveguide presented by the antenna feed to the impedance of two, 50-ohm, coaxial transmission lines over an octave bandwidth. A square OMT structure was chosen instead of a circular structure because the single-mode bandwidth is wider and it is easier to manufacture. The high impedance, square waveguide port of the OMT tapers to a quadruple-ridge waveguide with an impedance near 50-ohms. A shorting structure in the quad-ridge waveguide behind the coaxial probes provides dominant-mode impedance matching while allowing in-band, higher-order modes to propagate through to the back of the device and into an absorber. This prevents trapped-mode resonances from occurring which would have otherwise resulted in sharp suck-outs in the frequency response, a common problem in quad-ridge OMTs.

Each quad-ridge OMT consists of two pairs of machined fins and identical cast or machined shells for the four corner pieces. The design of the OMT provides for repeatable fin spacings and allows each device to be easily tuned simply by adjusting the length of the coaxial probes. The L-band OMT is 69.62 cm long (corresponding to 2.32λ at the lowest frequency of 1 GHz) while the length of the C-band OMT is 21.40 cm (2.85λ at 4 GHz). All the OMT designs have been found to perform well and meet or exceed specification. The S-band OMT, for example, has a measured return loss of less than -21 dB, an isolation better than -40 dB, and a warm insertion loss of -0.2 dB.

The right and left-circularly polarized components of the received radiation are separated in a combination of the quad-ridge OMT with a coaxial 90° quadrature hybrid coupler. The signal paths between the OMT and the hybrid coupler are phase-matched to within $\pm 1^\circ$ in the center of the band. The amplitude balance between the two signal paths is better than 0.2 dB. The octave quadrature coupler is a commercially-available device that functions reliably at cryogenic temperatures.

For the Ku, K and Ka-bands, the circular polarizers are pure waveguide devices. They use a corrugated, waveguide phase-shifter [11] followed by a twofold-symmetric, orthomode junction that was introduced by Boïfot [12]-[14]. The phase-shifter provides the 90° phase-shift required to convert circular into linear polarization and typically has less than a $\pm 5^\circ$ phase error across the band. The symmetric OMT can be easily manufactured as a split-block with conventional machining techniques. The combined insertion loss of this style of polarizer is less than -0.3 dB across its operating bandwidth. The return loss is typically better than -20 dB and the isolation exceeds -40 dB. For the Q-band receiver with its relatively narrow bandwidth ratio (25%), the circular polarizations are extracted with a commercially-available, sloping septum polarizer [15].

The development of an 8-12 GHz OMT for the X-band receiver is still in progress. Due to cryostat size and compressor capacity constraints, the ideal solution would be a new OMT

that could be inserted directly into the existing VLA 8.0-8.8 GHz cryostat with minimal modifications. A planar OMT [16]-[18] may be the only design that will allow this option to be viable. This type of design replaces the coaxial probes with a four probe microstrip circuit that requires two 180° hybrid couplers to combine the signals from opposing probes, as well as a 90° hybrid to generate the left and right circular polarizations from the two orthogonal linear polarizations. While the benefits of the small size and weight of a planar OMT approach are obvious, it is yet unclear how its inherent resistive losses will affect its noise performance compared to a more traditional waveguide polarizer. Two types of planar OMT designs will be investigated - one using gold thin-film microstrip circuits while the second uses high temperature superconductors. An all-waveguide OMT design is also being developed in the event that the noise contribution in the signal path prior to the low-noise amplifiers is excessive. This device is based on an ultra-thin turnstile design [19]. Its lateral dimensions would require a new cryostat to be designed to accommodate it.

Low Noise Amplifiers

There are nine different types of low-noise amplifiers (LNAs) used on the EVLA, all of which were designed and built by the NRAO's Central Development Laboratory [20]-[22]. The primary active elements in the amplifiers are indium phosphide, heterostructure, field effect transistors (InP HFETs) manufactured by TRW (now Northrop-Grumman Space Technology) under the NASA-led Cryogenic HEMT Optimization Program managed by the Jet Propulsion Laboratory, and obtained by the NRAO under special agreement. All the HFET devices used in the input stage of the EVLA amplifiers are from the so-called "Cryo-3" wafer which exhibits record performance when compared to all other manufacturing runs of similar devices. In the 4-100 GHz range, the cooling of an InP HFET typically reduces the internal amplifier noise to within 4 to 6 times the quantum limit [23].

The development of coolable LNAs requires detailed knowledge of both the signal and noise models of HFETs at cryogenic temperatures. These models have been developed with sufficient accuracy to achieve designs with optimal noise bandwidth performance [24],[25]. The design of the latest generation of amplifiers used for the EVLA was largely built upon the success of the LNAs created by the NRAO for the Wilkinson Microwave Anisotropy Probe project. The use of "chip and wire" technology allows for the best performing HFET devices to be chosen from the wafer to be employed as the input stage of the amplifier, thus ensuring a superior noise figure while avoiding a repeatability problem that is often observed in devices at cryogenic temperatures from different parts of the wafer or from different wafers. Single-ended amplifier designs are used for most of the frequency bands, with the C, X and Ku-band LNAs having three gain stages while the K, Ka and Q-band designs utilize four.

Most of the receivers have cryogenic isolators located on the input of each LNA to provide an adequate input impedance match. This is necessary in order to diminish standing waves in the front-end optics as well as to reduce cross-channel leakage in the circular polarizer. Since octave-wide cryogenic isolators are not commercially available at L or S-bands, NRAO developed several balanced amplifier designs with input return losses better than -15 dB. For L-band, the 1-2 GHz LNAs are built as “gain blocks” with 18 dB of gain. Two cascaded gain blocks are used per channel (for a total of four amplifiers in each cryostat). The first, “low-noise”, balanced amplifier uses InP HFET transistors to achieve a noise temperature of about 4K. The second, “high-power”, gain block uses commercial, pseudo-morphic HFETs to achieve a 1 dB compression point in excess of +13 dBm, but with a higher noise temperature of about 20K. This configuration provides the best compromise between low-noise and high dynamic range. It also ensures that the broadband cryogenic amplifiers are unlikely to saturate from strong RFI before the signal reaches the warm post-amplifiers outside the cryostat. A novel 2-4 GHz balanced amplifier that uses a total of four InP HFET devices was developed for S-band. Each of the quadrature signal branches contains two gain stages operating in series. They are amplitude and phase matched to provide the desired gain and high input and output return loss performance.

Each EVLA receiver has a gain of about 35 dB inside the cryostat with an additional gain of 25 dB or more in the room temperature RF section outside. This portion of the signal chain is relatively straightforward in most of the EVLA receivers and consists of commercial isolators, filters, post-amplifiers, and mixers.

Each of the new EVLA receivers is contained in its own cryostat which is cooled by a CTI Model 350 refrigerator. Model 22 units are used for cooling the existing X and Q-band receivers, which have the smallest cryostats of the eight receiver bands. The entire signal path, including the polarizers and the low-noise amplifiers, is cooled to 15K, except at L and S-bands where the large polarizers are cooled only to 50K.

MMICs

Both the Ka and Q-band receivers make use of monolithic microwave integrated circuits (MMIC) in their room-temperature signal chain. The Department of Electrical Engineering at the California Institute of Technology was contracted to design a 40-50 GHz filtered post-amp for Q-band and a 26-40 GHz downconverter for Ka-band [26], [27]. These modules used custom metamorphic-HEMT low-noise amplifiers, which are InP pHEMT devices on a GaAs substrate, fabricated by Raytheon. The broadband downconverter for the Ka-band receiver also has a number of commercial MMIC amplifier chips, as well as a custom double balanced mixer and a LO tripler fabricated by United Monolithic Semiconductor using their GaAs

Schottky diode technology.

Receiver Headroom

In order to avoid the adverse effects of non-linearities which may arise in any of the active components (such as amplifiers, mixers or solid state attenuators) in the signal path when driven into compression, the EVLA front-ends and downstream IF circuitry were designed to ensure that the standard operating point is well below the saturation level of any device. This is a delicate balance since the signal must also be well above the noise floor of the various amplifiers in the RF/IF chain to ensure the overall system temperature is not degraded. The headroom specification for the EVLA is to have all active components operating at least 20 dB below their 1% compression points (which corresponds to being about 32 dB below the 1 dB compression point) when the antenna is looking at cold sky. The impact of insufficient headroom will only become a major limitation in the presence of strong RFI, where unwanted harmonics and intermodulation products generated in the amplifiers or mixers may cause spurious signals to arise. It is expected that the 20 dB headroom specification will provide adequate dynamic range so that the effects of both existing and future RFI will not cause saturation.

3.2. Intermediate Frequency and Local Oscillator Systems

The LO and IF systems in the EVLA are highly flexible systems designed to support observations in two modes of operation. During the early construction phase of the project, the EVLA is required to operate in a transition mode where the new electronics must operate in conjunction with unmodified VLA antennas and provide signals to the existing VLA correlator. Later in the project, as more VLA antennas are converted to the EVLA design and the WIDAR correlator is brought online, the systems will be able to easily switch between this transition mode and the final EVLA mode of operation. The transition mode will no longer be required once the original VLA correlator is decommissioned.

3.2.1. Intermediate Frequency System

The EVLA IF system (Figure 3) consists of three primary signal paths: one for the higher frequency bands (Ku, K, Ka and Q), one for the lower frequency bands (4, P, L, S and C), and one for X-band. All bands except X are converted to a common IF in the frequency range of 7.5-12.5 GHz. The signals from the EVLA X-band receiver, which

operates at 8 to 12 GHz, are routed directly into the main downconverters without frequency conversion.

The RF signals from the high frequency receivers are converted to IF as follows. The first IF conversion for signals from the K, Ka and Q-band receivers occurs in the receivers themselves. At this stage of the IF, the frequency of the signals lies in the range of 8-18 GHz. IF conversion does not take place in the Ku-band receiver, which delivers its 12-18 GHz RF signal directly to the telescope's IF system. The signals from all four of the high frequency receivers are then routed to a broadband UX converter module. In this module, IF signals in the frequency range of 7.5-12.5 GHz are amplified and routed directly to the module's output. IF signals in the frequency range of 11.5-18 GHz are amplified and downconverted to a 7.5-12.5 GHz IF using LO signals from the synthesizers discussed below.

Like the X and Ku-band receivers, no frequency conversion is performed in the 4, P, L, S, and C-band receivers. The 4 and P-band signals are combined and then routed to the 4P converter module where they are up-converted to the range of 1.0 to 1.4 GHz. These signals and those from the L, S and C-band receivers are routed to another conversion stage, in which the signals are up-converted to the 7.5 to 12.5 GHz IF frequency range, again using LO signals from the synthesizers described below.

Thus, signals from all receivers are converted to the 7.5-12.5 IF frequency range. In the final downconverter modules, the IF signal is bandpass filtered to 7.5-12.5 GHz and amplified. The amplitude of the IF signal is then leveled to a standard power by adjusting a 32-step attenuator. The leveled signal is then split into two paths. Each of these paths is converted to a range of 2048 to 4096 MHz using LO signals from a fine-tunable frequency synthesizer. These signals are routed into digitally controlled, 15 step, gain slope equalizers. The equalizers are used to compensate for slopes in the signal bandpass due to variations in the receivers, cables and upstream electronics. Compensating for the slope is very important because of the limited dynamic range of the 3-bit digitizers (see below). The outputs of these equalizers are passed through a second 32 step attenuator to set the levels required by the digitizers. The signals are output from the module through very sharp cutoff, 2048-4096 MHz, anti-aliasing filters and connected to the 3-bit digitizers in the modules for the data transmission system (DTS) which operate on a 4096 MHz clock. Note that elsewhere in this document the IF bandwidth is referred to as a nominal 2 GHz band, although in fact it is 2.048 GHz.

Additionally, one of the 2048 to 4096 MHz paths can be routed to an additional stage where it is converted by a 4096 MHz fixed LO signal to a range of 1024 to 2048 MHz. This signal is leveled by a 32-bit step attenuator, then output from the module through a sharp cutoff, 1024-2048 MHz, anti-aliasing filter. This is the input to the 8 bit digitizers in the

DTS module, which operate on a 2048 MHz clock. Gain slope equalization is not performed on this signal due to the greater dynamic range of the 8-bit digitizer.

3.2.2. *Local Oscillator System*

The local oscillator system (Figures 3 and 4) is based on 128 MHz and 512 MHz master reference signals, both from a crystal oscillator locked to a hydrogen maser and a 1 Hz, GPS-based, master timing signal. These signals are used to generate all other reference and timing information used by the EVLA system. With the exception of the maser, the master reference system is fully redundant to ensure high reliability and continued operations during maintenance.

Reference signals are distributed to an antenna over a single mode, fiber optic cable operating at the 1310 nm zero-dispersion wavelength. The reference signal consists of a 512 MHz sine wave with a phase inversion of 60 ns duration occurring once every 10 seconds as a timing reference. Absolute time is passed to the central and antenna electronics using the network time protocol (NTP) over the gigabit Ethernet employed by the EVLA’s monitor and control system. Precise time is obtained in the antenna by synchronizing the NTP time with the timing signals in the local electronics.

The phase of the reference signal to each antenna can change due to temperature and mechanical effects in the fiber. The change is measured by a round trip phase (RTP) system (Figure 4). The measurement is made by splitting the optical reference signal at the antenna and sending part of it back to the central LO system on a second single mode fiber in the same cable. This signal is then compared to a master reference signal to get the total phase change in the fiber. The result is divided by two to get the phase change at the antenna. Although there is no guarantee that the two fibers will behave exactly the same, experience indicates that they behave sufficiently similarly that the factor of two mentioned above is adequate for the needed accuracy. The accuracy of the phase measuring equipment is of order 100 fs, which is smaller than the relative delays introduced into the astronomical signals by the varying atmosphere above the antennas for most VLA baselines.

At the antenna, the optical signal is converted back to an electrical signal and routed to the antenna reference generator module (Figure 3). In this module, a crystal oscillator is phase locked to the incoming reference signal. The 128 MHz and 512 MHz signals from the oscillator are fed to two, step recovery diode-based, comb generators used to derive all of the higher frequency reference and LO signals in the antenna. In addition, a 60 ns timing pulse is extracted from the reference signal by a high speed flip-flop and fed into a field

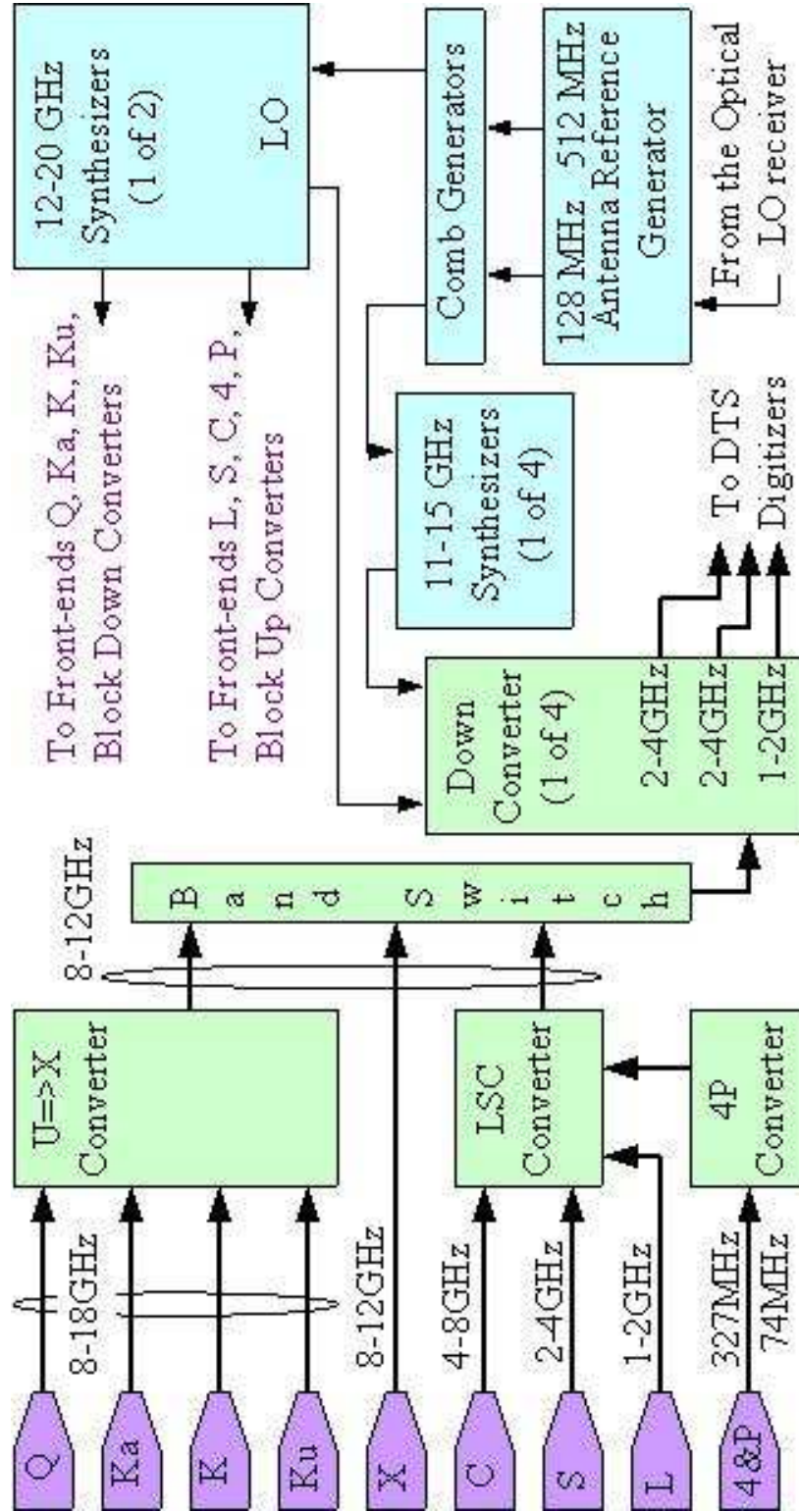


Fig. 3.— EVLA antenna LO-IF system

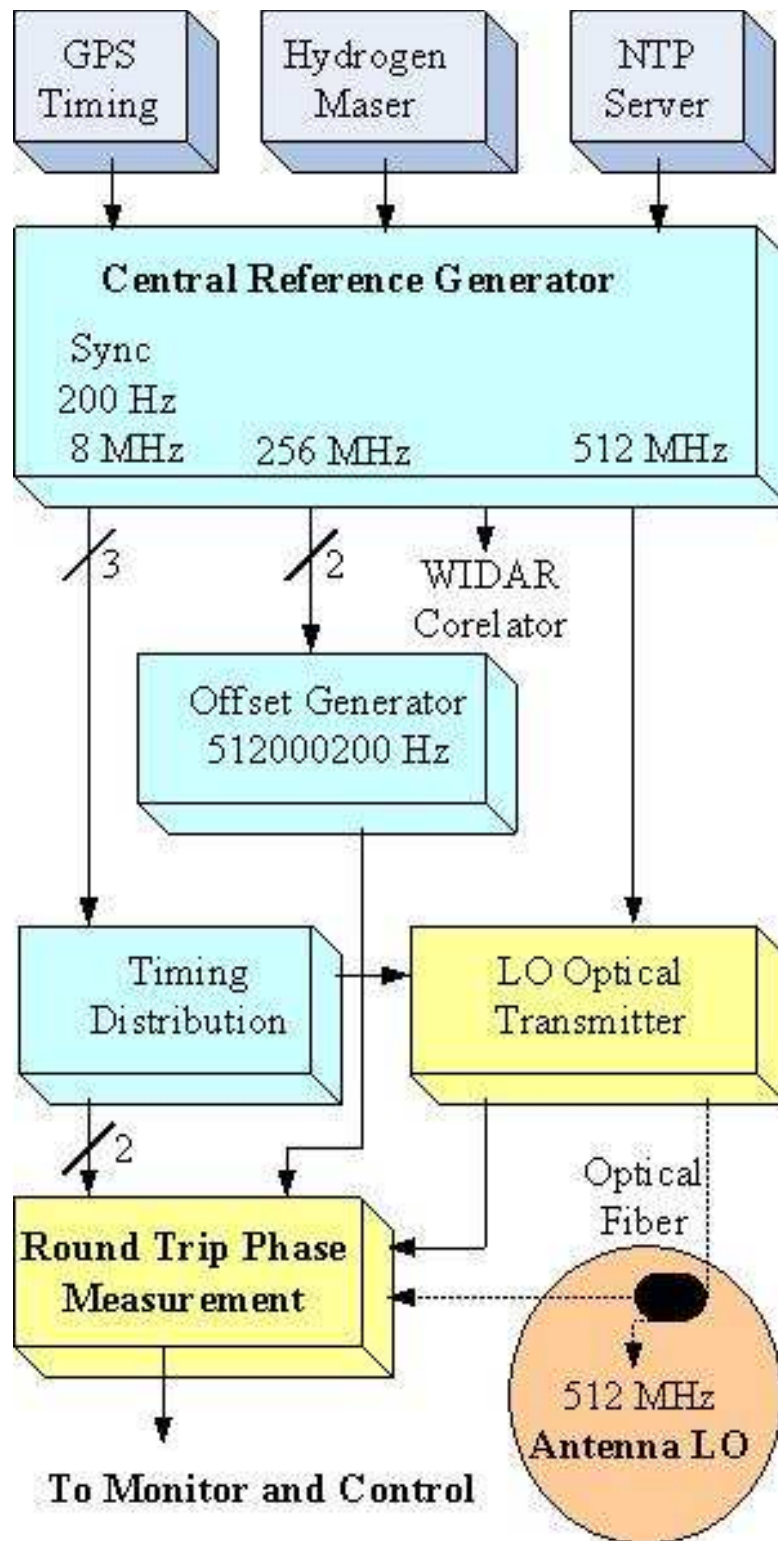


Fig. 4.— EVLA LO distribution system

programmable gate array (FPGA). This FPGA develops all of the various timing signals used in the antenna.

There are two types of synthesizers in the system (Figure 3). The LO signals to the receivers and/or converters for all bands except X-band are produced by a conventional Yttrium Iron Garnet (YIG) oscillator that is phase locked to a harmonic of the 512 MHz reference, offset by the 128 MHz reference, which produces tones in the frequency range of 11.776 GHz to 19.968 GHz in 256 MHz steps. Since the outputs of these synthesizers are used as the first (and in some cases second) LO, the synthesizers are designed to produce exceptionally clean, low phase noise CW signals with minimal harmonics. This is especially critical for the K, Ka and Q band receivers where the LO is multiplied by an additional factor of two or three inside the receiver.

The LO signals to the main downconverters are generated by the second type of synthesizers (Figure 3). These units are unique microwave synthesizers based on two YIG oscillators and two direct digital synthesizer (DDS) chips. The synthesizers produce tones in the frequency range of 10.8 GHz to 14.8 GHz in microhertz steps. The design of this synthesizer was very challenging because the phase of its output signal was required to be controllable as the frequency is changed. The fine tuning requirement for the synthesizer was necessary for the transition mode operation of the EVLA system. In this mode, the very fine tuning capability of the synthesizer is used to produce a differential rate between antennas to allow the interferometer fringes to track the source.

3.3. Data Transmission System

The EVLA data transmission system (DTS) digitizes the IF signals at the antennas and transmits them to the correlator located in the central control building. The DTS consists of a formatter module in the antenna, optical fibers between the antenna and the control building, and deformatters in the control building (Figure 5). The deformatters also include signal processing circuitry and digital-to-analog converters to allow the digital data produced by the EVLA antennas to be processed by the analog inputs to the existing VLA correlator during the transition period.

The data path from the antenna to the control building can be summarized as follows. An EVLA receiver can provide an instantaneous bandwidth of up to 8 GHz in each of two polarizations. The receiver output is partitioned into eight, 2 GHz wide, IF bands by the LO-IF system (Figure 5 shows two of the eight bands). Each IF band can be sampled with 4 GHz samplers at 3 bit resolution. Alternatively, the IF bands can be limited to 1 GHz bandwidth

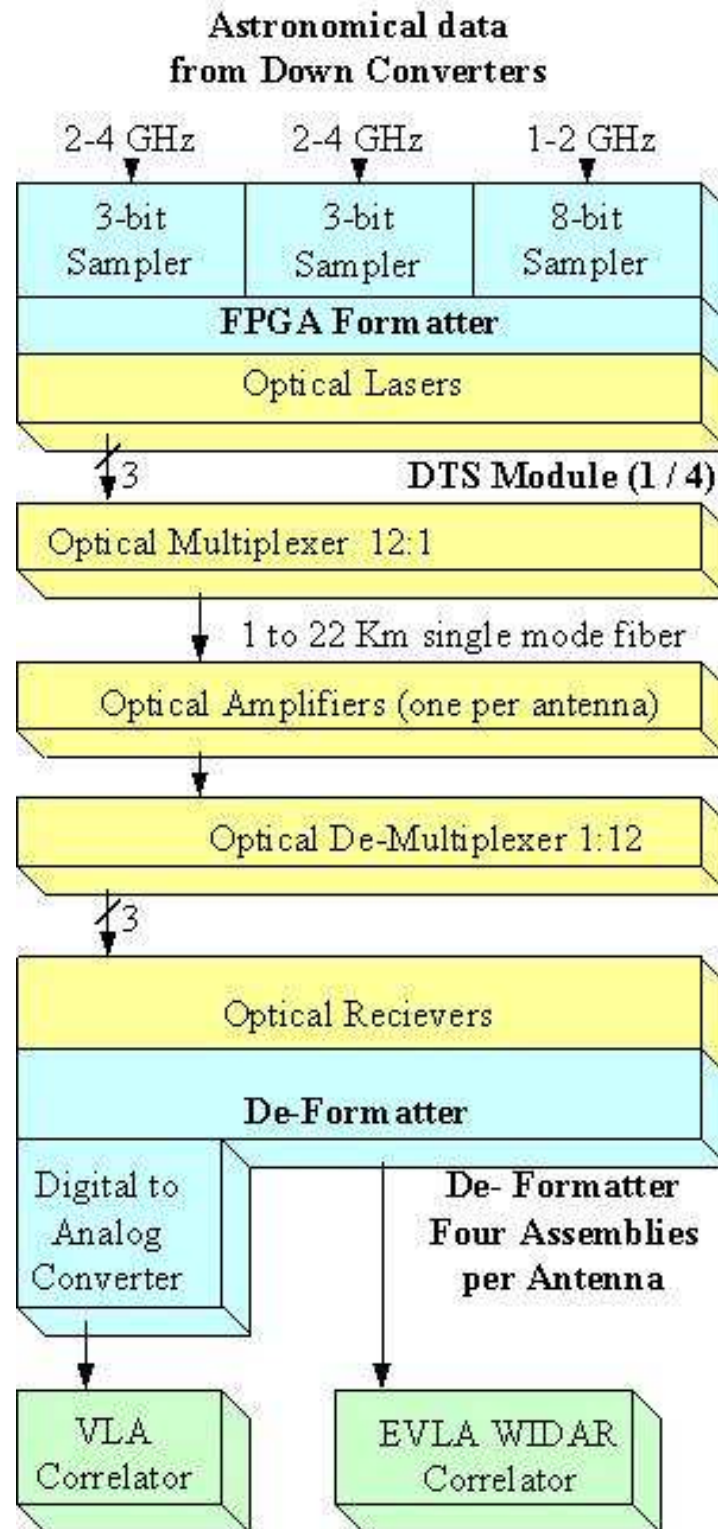


Fig. 5.— EVLA data transmission system.

and sampled with a single, 2 GHz, 8 bit device for observations with a high dynamic range in the input signals. This latter configuration is normally used for observations at 4/P, L, S, and C-bands. The digitizers incorporate a de-multiplexer that reduces the data rate to 512 Mbps on a parallel data path. A formatter receives the data from the digitizers and prepares them for shared transmission over three OC-192 fiber optic links at 10 Gbps each. The deformatter in the control building receives the three fiber optic signals and reorganizes the data into a format that is recognized by the new EVLA correlator.

The two 3-bit digitizers, the 8-bit digitizer, and the digital formatter are contained in a formatter module, and each antenna has a total of four formatter modules. The 8-bit digitizer is a 10 bit, analog-to-digital converter with a de-multiplexer chip set that is commercially-available from e2v. The 3-bit digitizer uses a 6-bit, 6 Gbps chip from Tele-dyne Scientific. The high speed de-multiplexing function is performed by serial-to-parallel converters from On Semiconductor. The formatter assembly consists of three FPGAs and three custom transponders. The FPGA receives data from the digitizers and splits the data stream into 128-bit payload frames. The FPGA also adds framing, timing, and error detection information. Since the EVLA DTS is unidirectional, it uses the specially constructed transponders to transmit the data on to three high-speed optical fibers. The data are transmitted on a fiber at 10 Gbps using 1550 nm lasers. The three data channels are completely independent apart from synchronization, monitor, and control signals, but all three are required to reproduce the sampled signal. The output data from the four formatter modules (i.e. 12 signals at 10 Gbps each) are combined onto a single fiber using dense wavelength division multiplexing (DWDM). This arrangement requires a different wavelength laser in each transponder.

A set of fibers runs to each of the 72 antenna pads throughout the EVLA. The cables are set in a star configuration with all fibers originating at the control building and ending at each antenna pad. The fibers for each antenna are grouped together in trunks and are terminated at each pad.

At the control building, the DWDM signal from each antenna is optically amplified and de-multiplexed onto 12 separate fibers. Each deformatter receives a set of three fiber signals from one of four formatter modules in an antenna and reorganizes the data into the format required by the correlator. The deformatter is physically installed in the correlator as a daughter card on the correlator's station board. (Architecturally, it is considered part of the antenna's electronics, instead of a component of the correlator). Each of these three signals is processed by an optical receiver and an FPGA. The optical receiver converts the optical input to a 10 Gbps electrical signal, which is de-multiplexed to a 640 Mbps data rate that can be accommodated by the FPGA. Logic in the FPGA identifies frame boundaries in the

input data stream and performs error detection and reporting with a simple parity check scheme. A 5-bit frame counter in the input frame format is used to synchronize the three channels. The data are then organized into the format required by the correlator.

A major requirement of the project is to continue scientific observations with the VLA as the EVLA electronics systems are installed. To accommodate this transition requirement, a digital filter was implemented in the deformatter FPGAs that selects a 64 MHz sub-band from the 1 GHz bandwidth available. The sub-band is converted to analog and passed on to the VLA baseband system (see Figure 5).

Digitization at the antenna avoids the distortions contributed by an analog transmission system, but raises concerns regarding self-generated RFI. Therefore, several features were implemented in the formatter module to suppress RFI. Packaging of the digitizers and associated electronics into a single formatter module avoids the routing of high-speed digital signals between modules and shortens signal runs. Clock signals and RF digitizer inputs enter the module via coaxial cables bonded at the module wall. Power to the module is provided by a single, heavily filtered, 48 volt supply. All operating voltages for electronics inside the module are obtained from regulators internal to the module. The high speed digital output data exit the module via three single-mode optical fibers. All fiber-optic signals penetrate the module wall through connectors chosen for their RF attenuation. The penetrations act as waveguides beyond cutoff and provide good shielding characteristics. The high-speed electronics in the module are cooled by air flowing through honeycomb RFI filters on the top and bottom of the module enclosure. The formatter module is heavily shielded. The main module enclosure consists of a welded aluminum box with one open end and the honeycomb filters attached on its top and bottom by screws with absorbing RF gaskets. The major electronics assemblies are attached to a single aluminum bulkhead that runs down the center of the module. Final assembly of the module consists of sliding the bulkhead into the box and securing its front cover with an absorbing RF gasket and a large number of screws. The shielding effectiveness of the entire assembly has been measured at 85 dB.

3.4. Correlator

The EVLA WIDAR (Wideband Interferometer Digital Architecture) correlator is the final destination for all of the real-time wideband signals carefully collected, down-converted, and sampled by all of the antennas. It calculates the cross-correlation function for every pair of antennas (baseline) in the array. This is no small feat considering the number of antennas in the EVLA (27), the bandwidths observed (16 GHz per antenna), and the 10^3 to 10^6 spectral channels needed per baseline.

The correlator is fundamentally an XF-type correlator, which has its roots in, and shares signal-processing elements with, a correlator [28] developed for the VSOP space radio telescope. An XF correlator cross-multiplies data from different antennas prior to the Fourier transformation to the frequency domain, as opposed to an FX correlator where the Fourier transformation precedes the cross-multiplication. More details on the fundamental signal processing for WIDAR are described in [29]. The correlator is sometimes referred to as an FXF style correlator, wherein the wideband signal is divided into smaller sub-bands with digital filters. Each sub-band is subsequently correlated in time and Fourier-transformed to the frequency domain. The sub-bands can be “stitched” with others to yield the wide-band cross-power result. Aliasing at the sub-band edges is greatly attenuated using offset LOs [29] in the antennas. The LO offsets also perform the equivalent of the Walsh function phase switching that is currently used at the VLA. Frequency offsets are typically 1 kHz, with a minimum of 100 Hz.

The primary feature of the EVLA WIDAR correlator is the large number of independently tunable sub-bands that are produced by digital filters implemented in FPGAs. The correlator is also robust to RFI given its large number of bits per sample and its filter reject-band attenuation. Each sub-band is tunable in location and bandwidth within the 2 GHz-wide basebands of the EVLA and can be assigned a flexible number of spectral channels. Tradeoffs can be made for bandwidth, number of spectral channels per sub-band, and field-of-view on the sky. The sub-band reject-band attenuation is better than 60 dB. 16K to 4M spectral channels can be produced per baseline, and the expandable 32-antenna correlator can process 496 baselines, each with 16 GHz total bandwidth. The correlator also contains high-performance pulsar “phase-binning” for “stroboscopic” imaging of pulsars. Additionally, it can produce the phased-array sum on the entire 16 GHz bandwidth of the array. The phased array mode is used primarily for producing data for very long baseline interferometry (VLBI) and pulsar observations.

The correlator consists of 16 standard 61-cm racks, each containing 16 large (38 cm x 48 cm) 28-layer, controlled-impedance, circuit boards of two types. A simplified diagram of the correlator, showing all key elements, is shown in Figure 6. The 128 station boards (StB) and 128 baseline boards (BIB) are connected by a distributed cross-bar switch to provide the flexibility described above. The signals traveling between the boards are 1 Gbps LVDS/PCML. A total of 512 high-speed data cables connect the racks, with each cable carrying approximately 10 Gbps of data and control and timing information. Buffers, embedded synchronization codes, and phase lock loops in FPGAs are used to eliminate the need for synchronization of clocks between boards or racks. Some minor restrictions apply compared to what a full cross-bar could accomplish; however, the cost and complexity of the distributed cross-bar are greatly reduced in comparison.

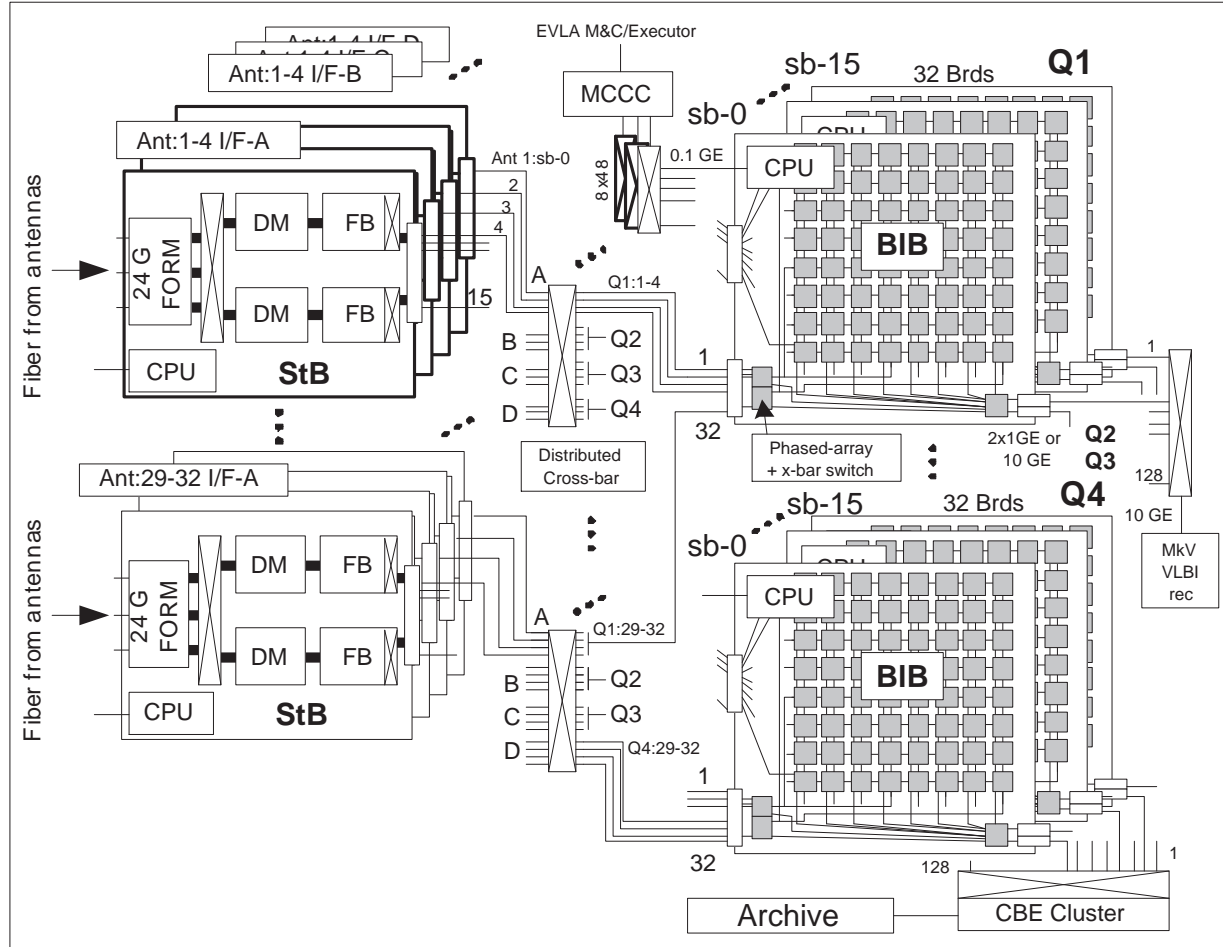


Fig. 6.— Simplified block diagram of the WIDAR correlator.

The WIDAR signal processing path is as follows. 96 Gbps of sampled payload data arrive from each antenna via optical fiber. As described in subsection 3.3, the data are sent to 4 StBs per antenna via the deformatter (the fiber optic receiver module (FORM) shown in Figure 6). An FPGA cross-bar allows these signals to be routed to two 64-bit wide, 256 MHz data paths on the board. Coarse delay tracking to within \pm one-half a sample is implemented with an FPGA and DDR SDRAM on a delay module (DM) mezzanine card on the StB. Baseline delay at the level of \pm one-sixteenth a sub-sample is implemented by continuous, real-time tracking of the residual delay error at the center of each sub-band using the correlator chip’s phase rotators [29]. The delay-corrected signals are then distributed to dual, 18-FPGA filter banks (FB). Each FB FPGA can further delay-correct the data to allow for a sub-band-specific beam delay-center offset on the sky. Each FPGA also contains four, 512-tap FIR stages with 16-bits carried between stages. One or all of the stages can be used to produce sub-bands from 128 MHz wide to as narrow as 31.25 kHz. Data exit the StB into the distributed cross-bar and is then routed to the BIBs. High-density, hardmetric connectors and mating cabling allow for 1.024 Gbps per pair of BIBs, fitting the numerology of the correlator nicely. The pair of BIBs processes all 32 antennas (496 baselines) for a sub-band pair (2×128 MHz), with 64 Gbps of astronomical data and up to 32 Gbps of control and timing data into each BIB. Signals are synchronized using dynamic phase alignment, re-timed, and distributed by two cross-bar and phasing FPGAs to the 8×8 array of XF correlator chips. The F672 BGA XF correlator chip is a 4 Mgate standard-cell device fabricated in 130 nm CMOS. Each device contains 2048 “lags”, each of which consists of a 4-bit multiplier, a 3-level phase rotator, and dual 22-bit accumulators. The phase rotators perform phase tracking (fringe rotation), sub-sample delay correction, and frequency shift removal. All signals for integration control originate in the StB, and integrations can be synchronized to system timing or any timing model, such as a pulsar ephemeris. Data from each correlator chip are integrated further in a low-cost LTA FPGA and DDR SDRAM. The final results are contained in UDP/IP packets, each containing 128 complex-lag accumulation results. The packets are sent to the correlator computing cluster on 1 Gigabit Ethernet via a commercial switch. The cluster carries out the data normalization, Fourier transform, and interference excision. The resultant data are sent to an archive for final image processing.

The crossbar FPGAs also perform the phasing of the antenna array. The phased signal is output to several destinations, primarily Ethernet packets to a VLBI data recorder.

The correlator also provides four, wideband, auto-correlation products for every base-band pair. Each data product has 1024 spectral channels, but with a factor of four sensitivity loss due to hardware limitations that arise from acquiring the auto-correlations in 64-lag chunks every 10 ms. Auto-correlations are also acquired in each sub-band with the cross-correlator hardware, although only two products at a time per antenna may be acquired.

Each StB and BIB contains a PC/104+ embedded processor mezzanine card running real-time Linux. PC/104+ is an inexpensive and high performance technology for this purpose. The StB computing requirements are the most stringent because real-time delay tracking and phase model generation, integration control, and data acquisition must be performed. The BIB computing requirements are less stringent, requiring only monitor and control operations since the flow of all correlation coefficient data is CPU-independent. This arrangement effectively eliminates any bottlenecks to the data flow.

The data rate produced by the correlator is governed by several factors. The correlator hardware is capable of producing data at an extremely rapid rate, so data rate limitations are set by a combination of factors, including configuration of the CBE computers, their performance and network topology, and not least scientific necessity. The standard correlator configuration is a 1 Gigabit Ethernet link from each of 128 BIBs for the visibility data, providing the capability for dumping all spectral channels every 11 ms, and a 1 Gigabit Ethernet link from each BIB for real-time phased data. Thus, the maximum data rate to the computing cluster is 128 Gbps. A BIB can be upgraded with 10 Gigabit Ethernet for a maximum data rate of 1.28 Tbps. With the planned number of CBE computers, all spectral channels can be dumped every 100 ms, for a data rate of 167 mega-visibilitys per second in a 32-station correlator. The actual dump times used will be determined by science objectives, array configuration, and data storage capabilities. On the timescale of early 2012, typical data rates produced by the correlator are expected to be at the more modest rate of about 20 MBps, with a maximum rate of 75 MBps.

3.5. Software

One of the major goals of the EVLA project was to replace the software of the VLA, much of which was written over 20 years ago and was becoming more and more difficult to maintain. The new hardware of the EVLA requires much more software to control it, and because the instrument is so much more capable than the VLA, the control and user software is necessarily more complex. While more complex, the intent of the new software in the end is to make the process of observing with the EVLA much more accessible to the astronomer who is not necessarily intimately familiar with the theory and techniques of radio interferometry.

The EVLA software is divided into two major areas: the control and monitoring of the hardware, or Monitor and Control (M&C), and the software generally accessed by the user, or User Software. Figure 1 shows a very high level view of the EVLA software system, along with how it fits in with the hardware, and with the information flow highlighted. Two

overriding principles guide the implementation of the software. First, the software must be loosely coupled, so that if a particular subsystem is not functioning, the rest can continue to run. Second, the software must make it easier to use and operate the EVLA, including lack of human intervention where possible.

3.5.1. *Monitor and Control Software*

The EVLA monitor and control software design concept is a highly distributed, loosely coupled system. Most hardware modules contain a fairly capable, single board computer system, the Monitor/Control Interface Board, or MIB (for the correlator, called CMIBs, for Correlator MIB). The MIBs receive commands via datagram (under the UDP protocol) from the central system, and send monitor data by datagram to a central location, which archives it in a general purpose database. The MIBs also support a telnet protocol, which provides a useful debugging interface. Commands sent to devices/MIBs are labeled with a time at which they are to be executed. They are typically sent to the devices several seconds in advance, so the central entity itself does not, normally, have serious real-time deadlines to meet. Because self-generated RFI is a major problem for a sensitive, broad band radio receiving system, a central consideration for the MIB design was the minimization of generated RFI. For that reason, a system-on-a-chip was chosen, rather than the more common design with memory on an adjacent chip. MIBs also perform limit checking on the monitor points available to them. If a monitor point falls outside the range of permitted values, an alert is sent by datagram. These alerts are classified as to whether they are informational, require telescope operator action, or cause the data to be flagged as bad.

There are six central elements of the overall control system:

- The software on the MIBs themselves, which makes the individual modules within the system rather intelligent.
- The observing general manager, called the Executor. Within the Executor is a set of objects which are in one-to-one correspondence with the physical antennas. These objects are the mechanism by which all commands are sent to the MIBs in the antennas, and contain the code which converts a more generic description of the desired observation setup into commands to the MIBs associated with the antenna. The Executor operates on scripts, which allows for full scripting control by the observation setup software or astronomer.
- The entity which receives broadcast monitor data from the MIBs and elsewhere. It stores data in a general purpose database (currently Oracle). Web-based retrieval tools

are provided to extract and list or plot the data. There are about 300 monitor points on each antenna, and about 6 million rows per day are stored in the database.

- The alert server receives the alerts generated by the MIBs and other parts of the system, and classifies them as described above.
- The entity which annotates data with the system state and setup is called MCAF (Metadata Capture And Format). It gets data from the Executor (via XML records broadcast by the Executor), from the alerts-server (for information about whether data is valid for each antenna), and from other parts of the system.
- The entity which analyses output data in real-time is called Telcal. Real-time analysis is required for correcting antenna pointing and for solving for phases for use of the VLA as a VLBI element by coherently summing the signals from the antennas. It is also very useful to have it report system sensitivities during observations of calibrator sources as a general, telescope operator-accessible indication of the system health.

In addition, the correlator (WIDAR) requires several major software elements:

- CMIB software, which is similar to MIB software, allows even the lower level hardware modules to be relatively intelligent.
- The Correlator Back-End (CBE) software, which collects the data from the station and baseline boards and combines them into the fundamental data format for storage, the Binary Data Format (BDF). The CBE software does the Fourier transform from lags to spectra, spectral windowing, data blanking, sub-band stitching, and other tasks.
- The software on the main correlator control computer, which allows for communication with the rest of the EVLA software system. This communication is all done via documents in the eXtensible Markup Language (XML) which conform to a particular protocol (the Virtual Correlator Interface, or VCI).
- The software controlling the power distribution to the various parts of the correlator hardware. Although this software is relatively simple, it deserves mention because power control within the system is so important.

As mentioned, the system as a whole is loosely coupled. System components communicate via datagrams (sending either an internally developed command format or XML documents) or via the http-based REST protocol. Any system component can be stopped and restarted with minimum impact on the rest of the system, and normal operation will

return shortly after a system component is restarted, as soon as a set of commands to that component has been sent.

3.5.2. *User Software*

The EVLA user software encompasses all software that the user directly interacts with, as well as software that impacts the scientific output of the instrument. The user software is designed to be easy to use, with modern graphical user interfaces (GUIs) where needed. The user software, like the M&C software, is designed to be modular, so that major subsystems do not depend on each other to run. Information is passed between subsystems either via storage to and retrieval from a database, or direct passage of XML documents. This makes it so that transcription of information by hand, either written or computer, is not necessary.

There are five main subsystems of the user software:

- The entity for proposal creation, editing, submission, and handling, called the Proposal Submission Tool (PST). This tool allows potential users to propose for observing time on the EVLA, and for the evaluation of those proposals by the observatory.
- The entity for creation of observing scripts which give the details of sources to be observed, the instrumental setups, and timing information, called the Observing Preparation Tool (OPT). The output from this tool is a Jython script to be input into the aforementioned Executor.
- The entity for deciding which of all possible observing scripts available for observing should actually be observed at a given point in time, called the Observation Scheduling Tool (OST). This tool takes into account the scientific priority of the scripts, the required and current observing conditions, and other constraints. This tool allows for observations to eventually be fully dynamically scheduled, i.e., no human intervention involved.
- The entity for access to data in the scientific archive, called the Archive Access Tool (AAT). This allows scientists to find their own proprietary data, or other public data, given any of various search criteria. Once found, data can be downloaded to the user computer, or sent to a data processing pipeline for reduction, and the results from that downloaded.
- The data post-processing software. This software element takes the fundamental measured interferometric quantity, the visibilities, and processes them into final images

or spectra (or image cubes, the combination of the two). It includes data editing, flagging, calibration (bandpass, flux density scale, complex gain as a function of time, etc.), and imaging, including self-calibration. Automatic data-processing pipelines are part of the more general post-processing software, intended to be initially developed by astronomers and then implemented within the package. All observations done in standard modes will be pipeline processed and the results placed in the archive along with the raw and calibrated visibility data.

This user software must be capable of supporting both expert users and those that are new to using the EVLA, or any radio interferometer. As such, it often has two interface styles, expert and novice. In most cases, these interfaces are GUIs, either web-based, or stand-alone, using modern software tools (for instance, most of the web-based GUIs are written within the JavaServer Faces (JSF) framework).

4. Summary

The EVLA is a major expansion to the highly flexible and productive VLA. The expansion includes new or upgraded receivers that enable continuous frequency coverage from 1 to 50 GHz, a new broadband LO/IF system, a new fiber optic-based data transmission system, a new correlator to process the wideband data, a new monitor and control system, and new software that provides telescope ease of use. The expansion provides order of magnitude, or greater, improvements over existing capabilities with the VLA. Observations with the VLA have been ongoing as the expansion has progressed. The project is scheduled for completion in 2012. The expansion will enable new investigations into celestial radio transients, the evolution of objects in the universe, and the structure and strength of celestial magnetic fields.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The Dominion Radio Astrophysical Observatory is a National Facility operated by the National Research Council Canada.

Glossary of Acronyms

AAT	Archive Access Tool
BDF	Binary Data Format
BGA	Ball Grid Array
BLB	Baseline Board (in the WIDAR correlator)
CBE	Correlator Back-End
CMIB	Correlator Module Interface Board
CMOS	Complementary Metal Oxide Semiconductor
CPU	Central Processing Unit
DDR SDRAM	Double Data Rate Synchronous Dynamic Random Access Memory
DM	Delay Module (in the WIDAR correlator)
DTS	Data Transmission System
DWDM	Dense Wavelength Division Multiplexing
EVLA	Expanded Very Large Array
FB	Filter Bank (in the WIDAR correlator)
FIR	Finite Impulse Response
FORM	Fiber Optic Receiver Module
FPGA	Field Programmable Gate Array
GaAs	Gallium Arsenide
Gbps	Gigabit per second
GHz	GigaHertz
GPS	Global Positioning System
G/T	Gain-system Temperature quotient
GUI	Graphical User Interface
HEMT	High Electron Mobility Transistor
HFET	Heterostructure Field Effect Transistor
Hz	Hertz
InP	Indium Phosphide
IF	Intermediate Frequency
IP	Internet Protocol
JSF	JavaServer Faces
LNA	Low Noise Amplifier
LO	Local Oscillator
LTA	Long Term Accumulator
LVDS	Low Voltage Differential Signaling
kHz	kiloHertz
M&C	Monitor and Control

MCAF	Metadata Capture and Format
MBps	MegaByte per second
MCCC	Main Correlator Control Computer
MHz	MegaHertz
MIB	Module Interface Board
MMIC	Monolithic Microwave Integrated Circuits
NASA	National Aeronautics and Space Administration
NRAO	National Radio Astronomy Observatory
NTP	Network Time Protocol
OMT	Orthomode Transducer
OPT	Observation Preparation Tool
OST	Observation Scheduling Tool
PCML	Program Call Markup Language
PST	Proposal Submission Tool
REST	REpresentational State Transfer
RF	Radio Frequency
RFI	Radio Frequency Interference
RTP	Round Trip Phase
StB	Station Board (in the WIDAR correlator)
Tbps	Terabits per second
UDP	User Datagram Protocol
VCi	Virtual Correlator Interface
VLA	Very Large Array
VLBI	Very Long Baseline Interferometry
VSOP	VLBI Space Observatory Program
WIDAR	Wideband Interferometer Digital ARchitecture
XF	Cross multiplication/Fourier transformation
XML	eXtensible Markup Language
YIG	Yttrium Iron Garnet

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Table 1. Required Performance of EVLA Frequency Bands

Band	Center Frequency (GHz)	Frequency Range (GHz)	System Temperature (K)	Aperture Efficiency	Effective Temperature (K)	Maximum IF Bandwidth (GHz)
L	1.5	1-2	26	0.45	58	2x1
S	3.0	2-4	29	0.62	47	2x2
C	6.0	4-8	31	0.60	52	2x4
X	10	8-12	34	0.56	61	2x4
Ku	15	12-18	39	0.54	72	2x6
K	22	18-26.5	54	0.51	106	2x8
Ka	33	26.5-40	45	0.39	115	2x8
Q	45	40-50	66	0.34	194	2x8